Transverse Feedback in the HL-LHC Era

Presented by

Wolfgang Hofle

Transverse Feedback in the LHC High Lumi Era

Wolfgang Hofle
A. Butterworth, G. Kotzian, M. Jaussi, T. Levens,
K. Li, M. Ojeda-Sandonis, A. Rey, D. Valuch,
CERN
Beams Department

Acknowledgements: J.D. Fox, C. Rivetta, O. Turgut (SLAC) for US LARP

Outline

- LHC Run Transverse feedback system (ADT) and limitations
- Evolution of Transverse feedback until LS3
- Facing new challenges in the High Lumi era and options
- Conclusions

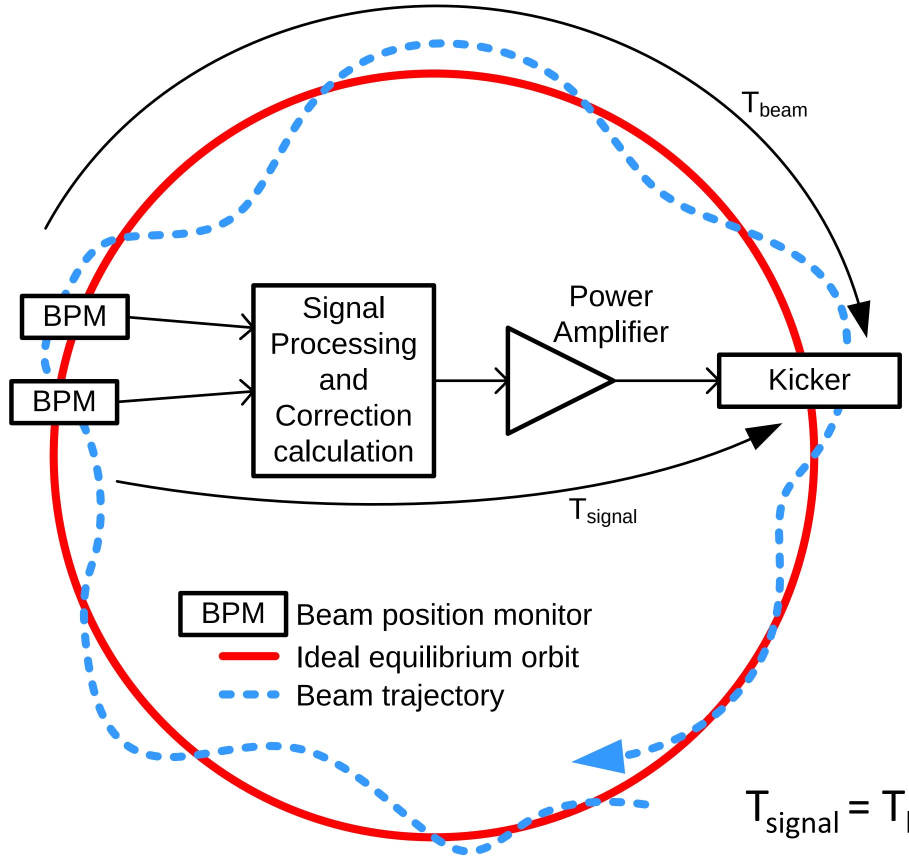
THE LHC RUN 1 TRANSVERSE FEEDBACK (ADT)

LHC Transverse Damper (ADT)

- Initially designed for
  - Injection damping
  - Feedback during ramp (coupled bunch instabilities)
- LHC Physics Run 1 (2010-2013)
  - Providing stability at all times in the cycle
    (including with colliding beams !)
  - Potential of ADT as a diagnostic tool to record bunch-by-bunch oscillations recognised
  - Abort gap and injection cleaning
  - Blow-up for loss maps and aperture studies
  - Tool to produce losses for quench tests
  - Potential to extract tune from feedback loop data (under development)

→ All these applications of ADT continue to be required for the High Lumi era

Principle of LHC Transverse Feedbacks



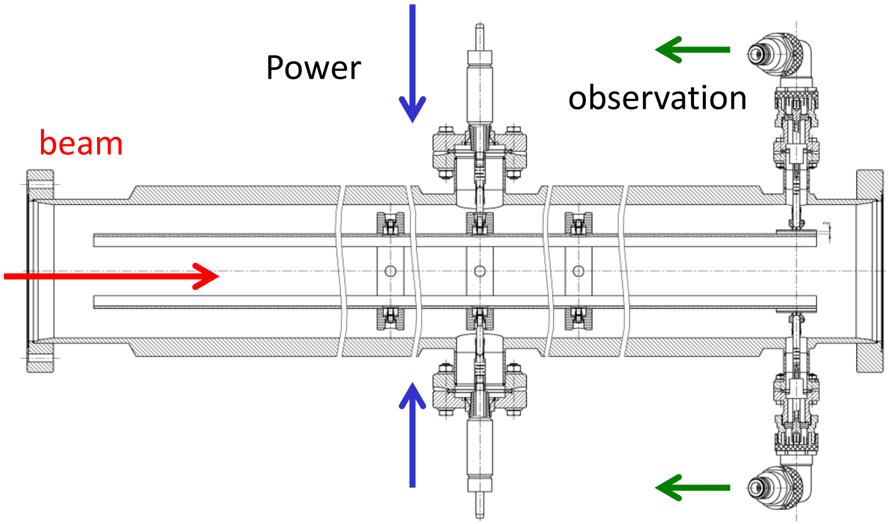
$$T_{signal} = T_{beam} + n\,T_{rev}$$

- Four systems: one per beam and transverse plane
- Initially two pick-ups per systems (8 in total)
- Total of 16 kickers (four per beam and plane)

LHC Transverse Damper Specs

Injection beam momentum	450	GeV/c
Static injection errors ($\beta = 183$ m)	2	mm
ripple ($\beta = 183$ m)	2	mm
resistive wall growth time	14	ms
decoherence time	68	ms
tolerable emittance growth	2.5	%
overall damping time	4.7	ms (53 turns)
standard bunch spacing	25	ns
lowest betatron frequency	> 2	kHz
highest frequency to damp	20	MHz
Electro-static kickers	base band	
aperture of kickers	52	mm
number of kickers per plane and beam	4	
length of kicker plates	1.5	m
nominal voltage up to 1 MHz	± 7.5	kV
kick per turn at 450 GeV/c up to 1 MHz	2	μrad

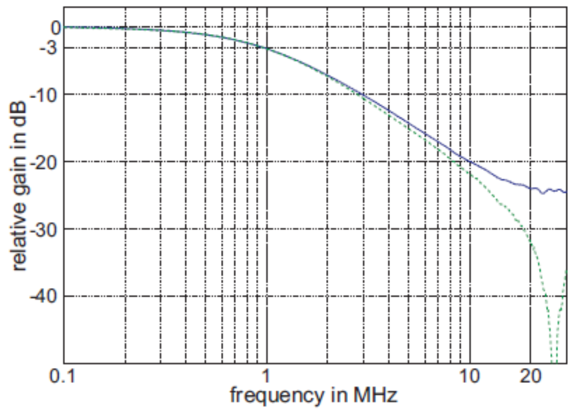
ADT Power and Kicker System



ADT kicker. The beam is kicked by electric field

- Kicker length: each kicker 1.5 m
- Max voltage: 10.5 kV
- Gain up to beyond 20 MHz
- 16 kickers
- 32x30 kW tetrode amplifiers
- Bandwidth up to 20 MHz
- Replacement by solid state system not obvious (prepare for tetrodes becoming obsolete during next 20 years ?)

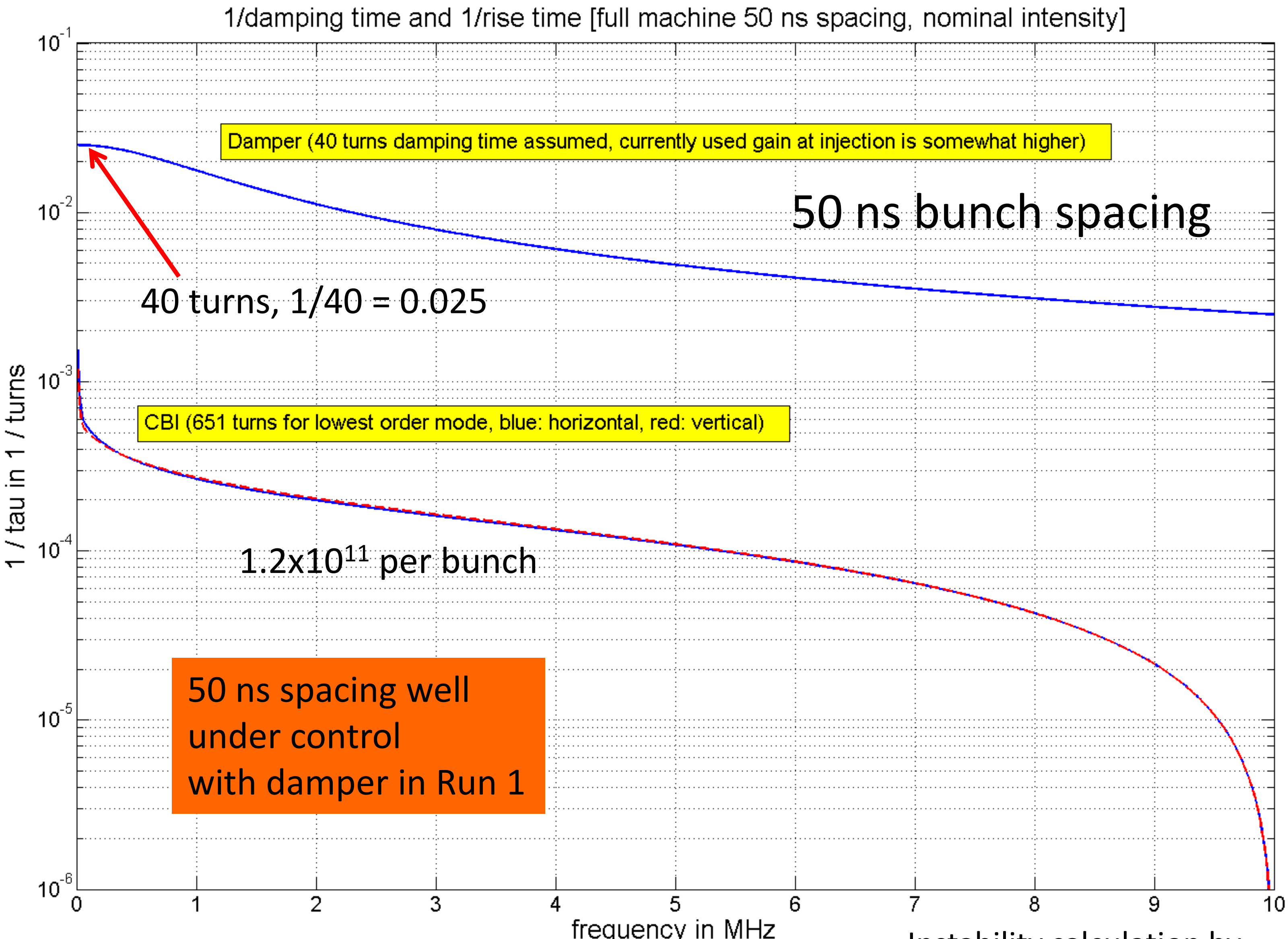
LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46



Measured ADT frequency response. Green: bare power amplifier, blue: power amp + kicker.

Built in collaboration with JINR, Dubna, Russia; E. Gorbachev et al. LHC Proj. Rept.-1165 CERN (2008)

Instability Growth Rates versus Damping



Instability calculation by
N. Mounet (CERN BE-ABP)

Drive Signal Generation

Under ground cavern

- 200 W driver amplifiers (25 MHz BW)
- tetrode amplifier control

EMC

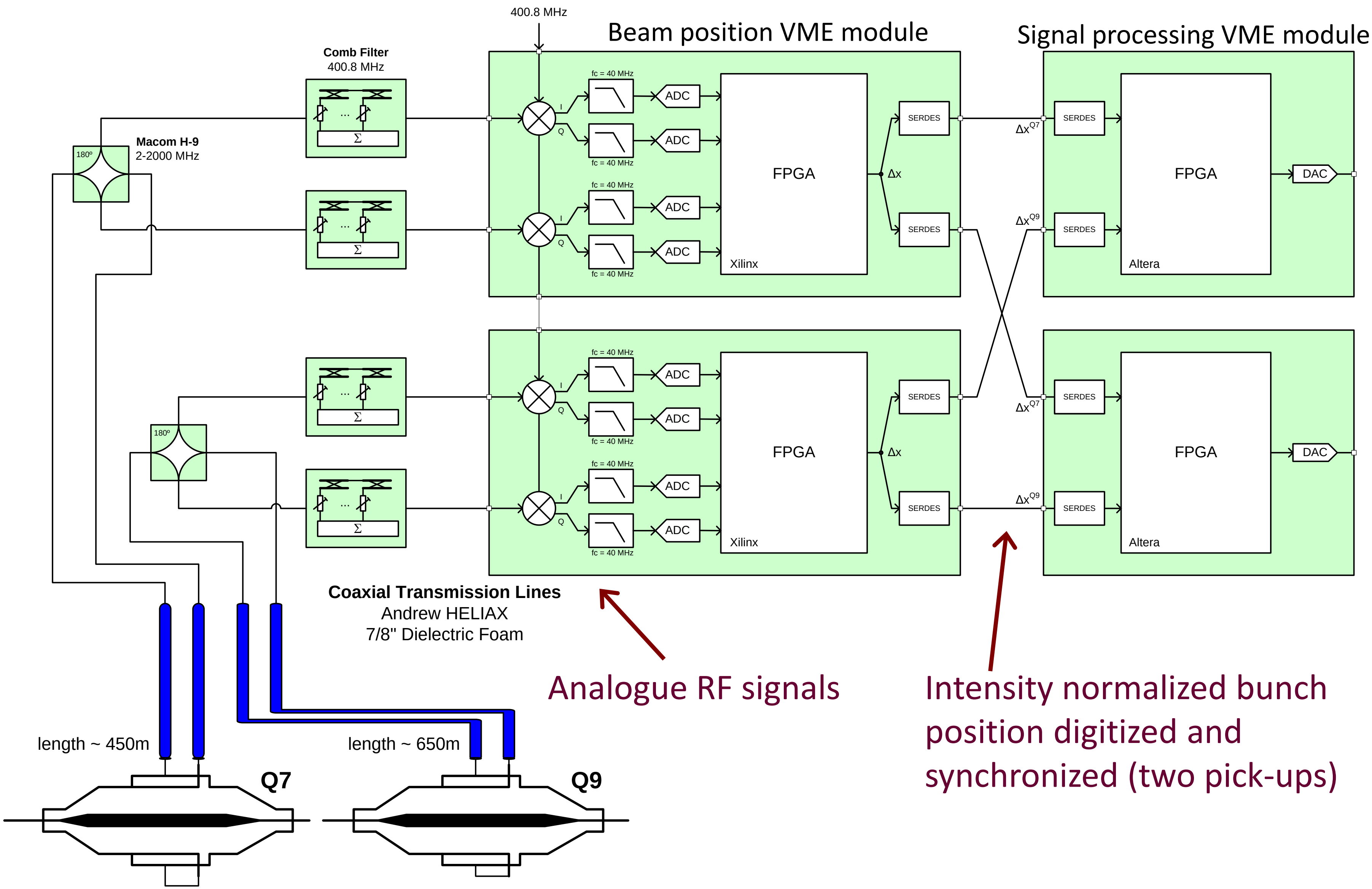
- carefully designed to minimize
- perturbances by noise
- major EMC issue during initial commissioning:
  8 kHz switching frequency of UPS

Electronics in surface building SR4
for easy access during commissioning

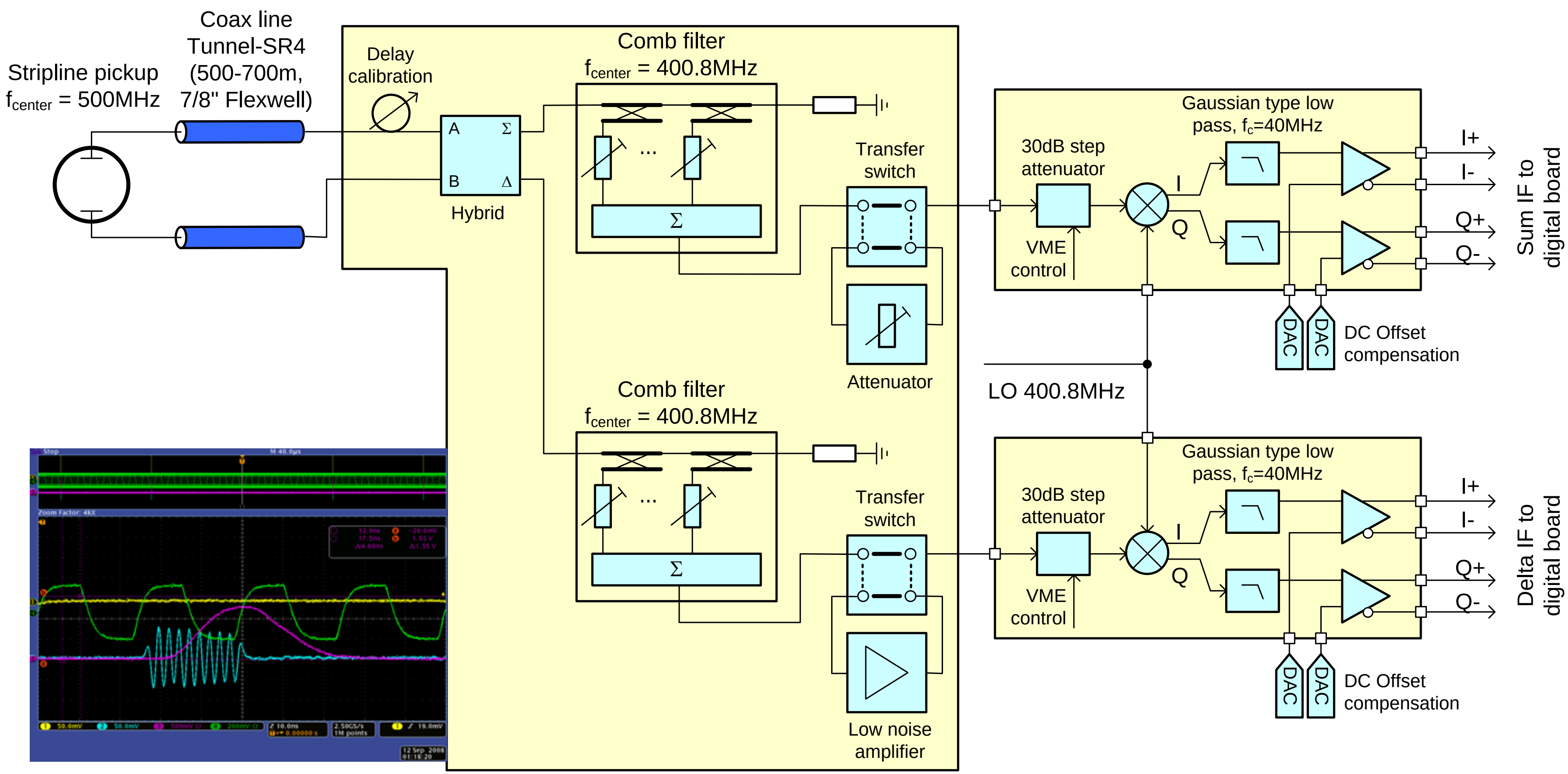
- A/D conversion
- all signal processing and D/A
- computer controls

Expect consolidation needed
to run until 2035

Overview of ADT Signal Processing

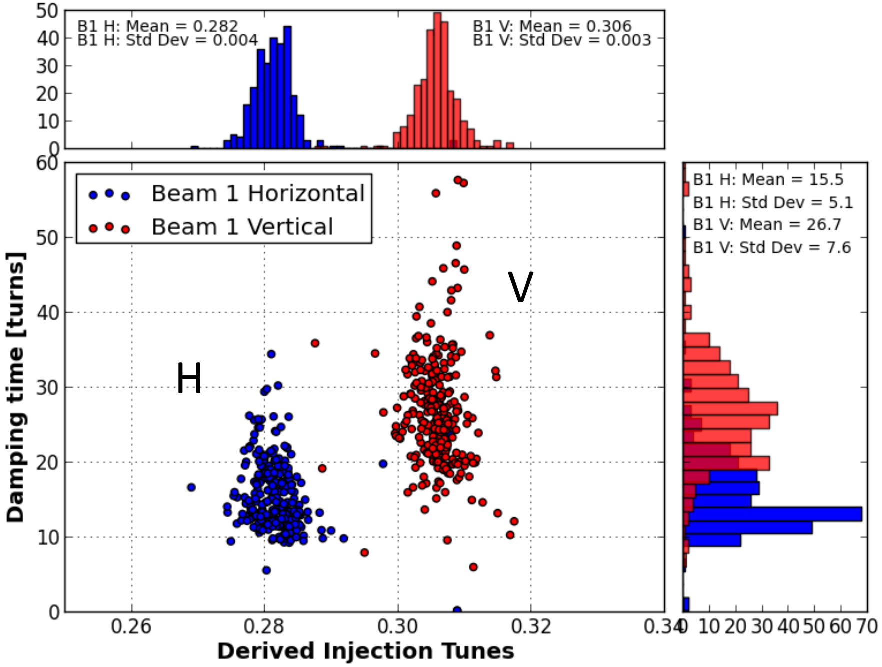


Beam Position Module



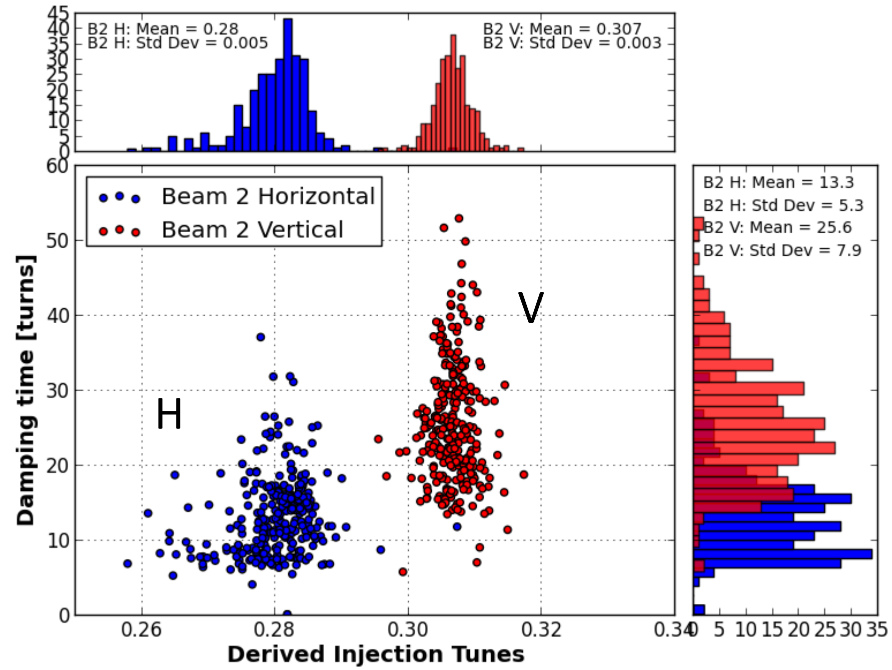
- Low noise amplifier for for good S/N ratio before digitization
- Adaptation of signal levels to beam intensity
- Challenge for multi-bunch operation: keeping reflections under control
- Key electronics determining system performance

Automated Fill Analysis: Damping Time Run1



Beam 1
H: 16 turns
V: 27 turns

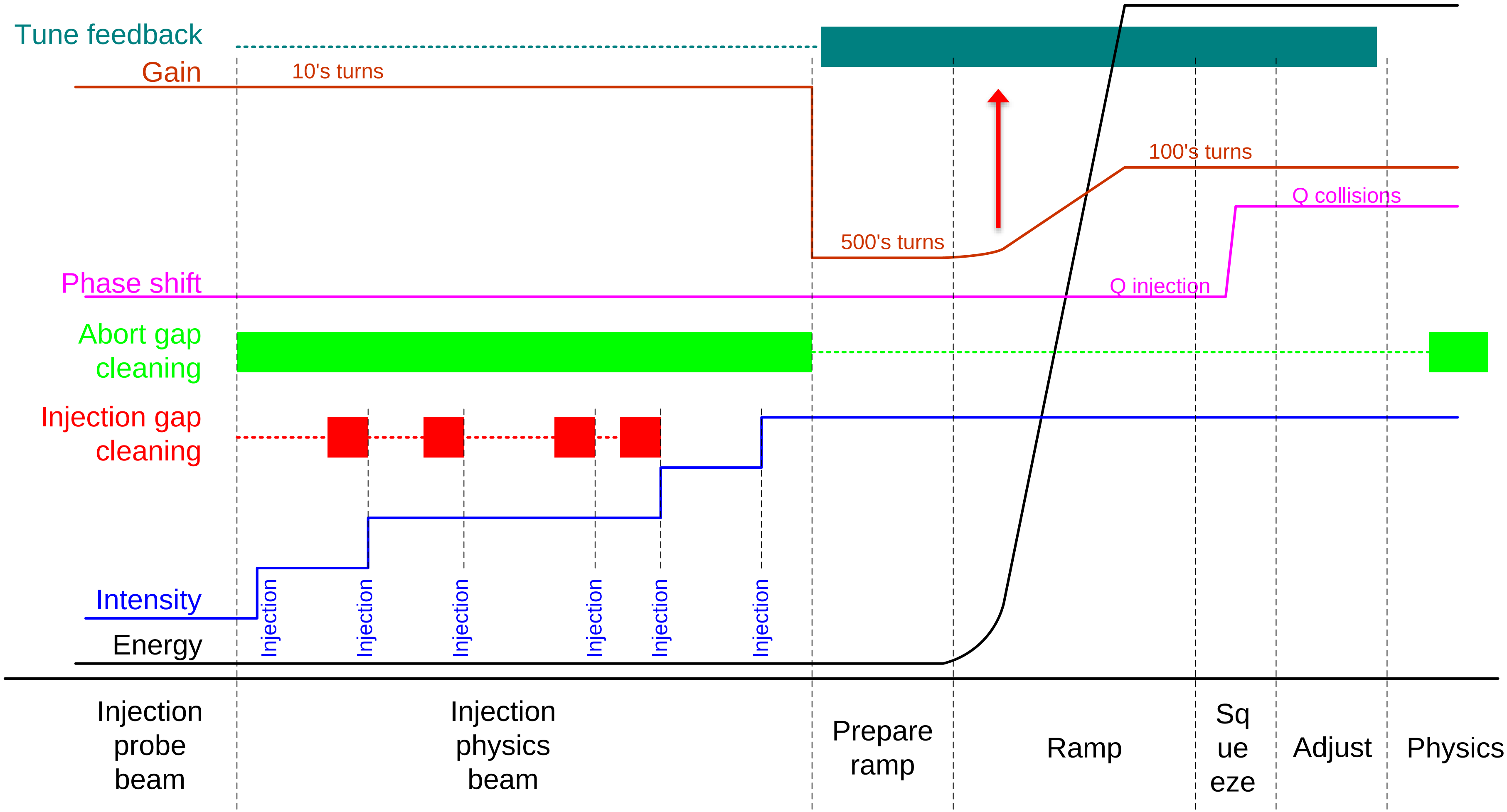
Beam 2
H: 13 turns
V: 26 turns



A. Macpherson
CERN BE-OP & BE-RF

450 GeV, first bunch of train injected is recorded

Operation Through Cycle



LHC

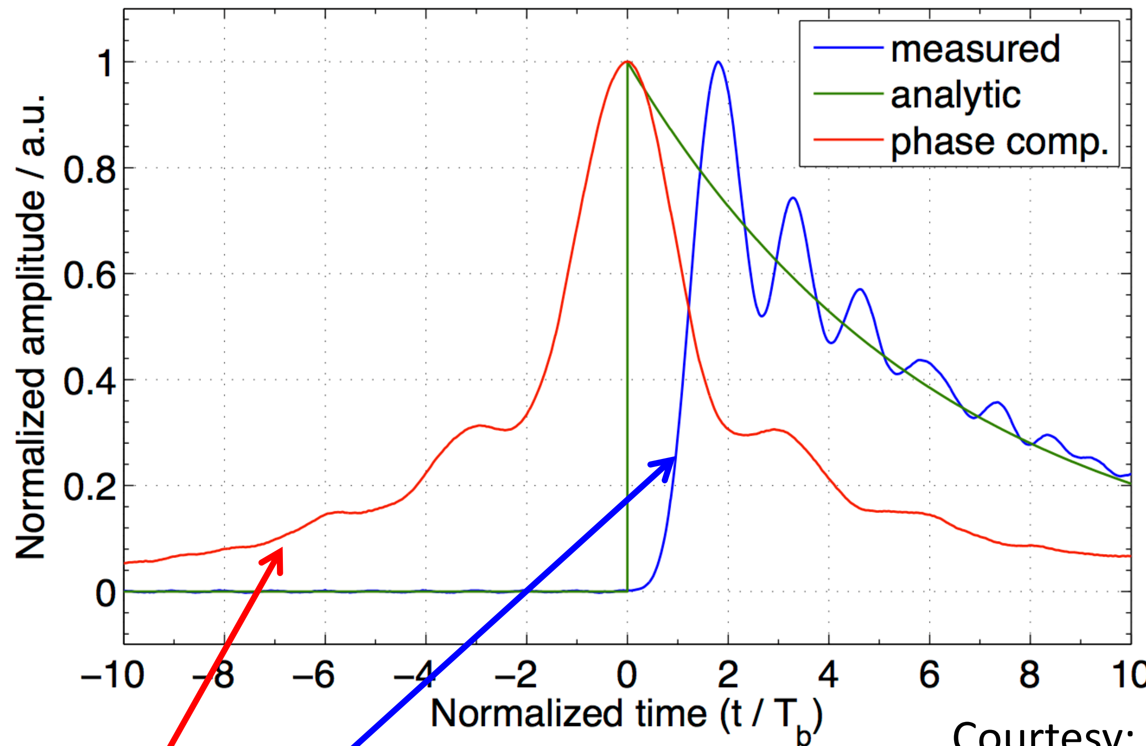
EVOLUTION OF ADT SYSTEM TOWARDS HIGH LUMI ERA

Limitations of current ADT system

- Kick strength → not a limitation
  - Sufficient strength
    - for injection oscillation damping
    - Abort gap cleaning and injection gap cleaning as regularly used
  - No change of parameters foreseen for High Lumi (energy, injection error, spacing of batches)
- Bandwidth → limited and a constraining
  - Damping of Single bunch instabilities
  - Rise-time, limits selectivity with respect to bunches (blow-up, cleaning etc.)
  - Tune sensitivity
  - → Signal processing can be used to tailor the time domain response, but at expense of kick strength
- Noise → contributes to emittance increase
  - Effect not easy to disentangle from other sources of blow-up
  - → Mitigating by upgrades of electronics and use of more pick-ups

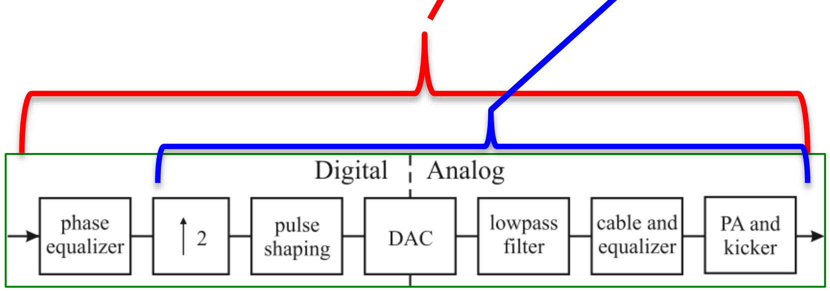
IMPROVING THE BANDWIDTH AND TIME DOMAIN RESPONSE

Impulse Response – Linearization of Phase



Courtesy: G. Kotzian

Linearization of phase makes system usable as feedback up to 20 MHz



32 tap FIR
for phase equalization

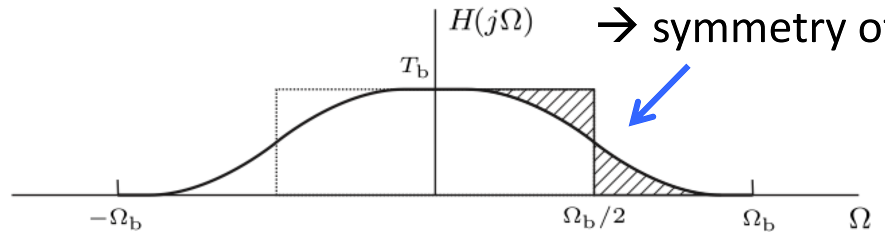
LHC

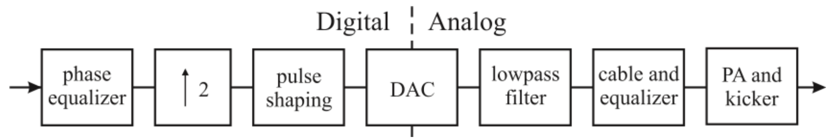
W. Hofle et al., IPAC'13, WEPME43

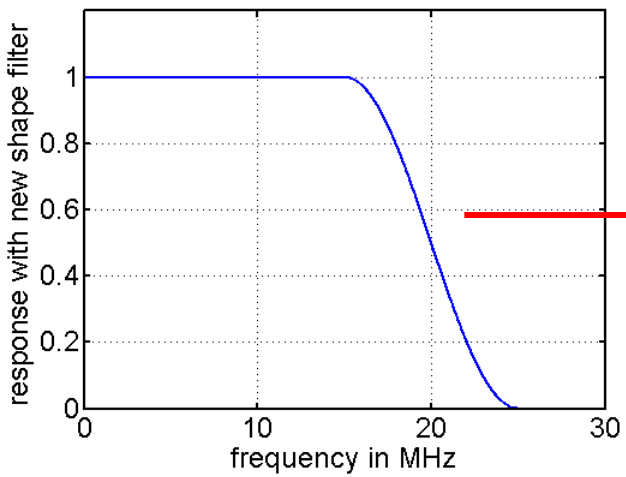
Shaping Time Domain Response

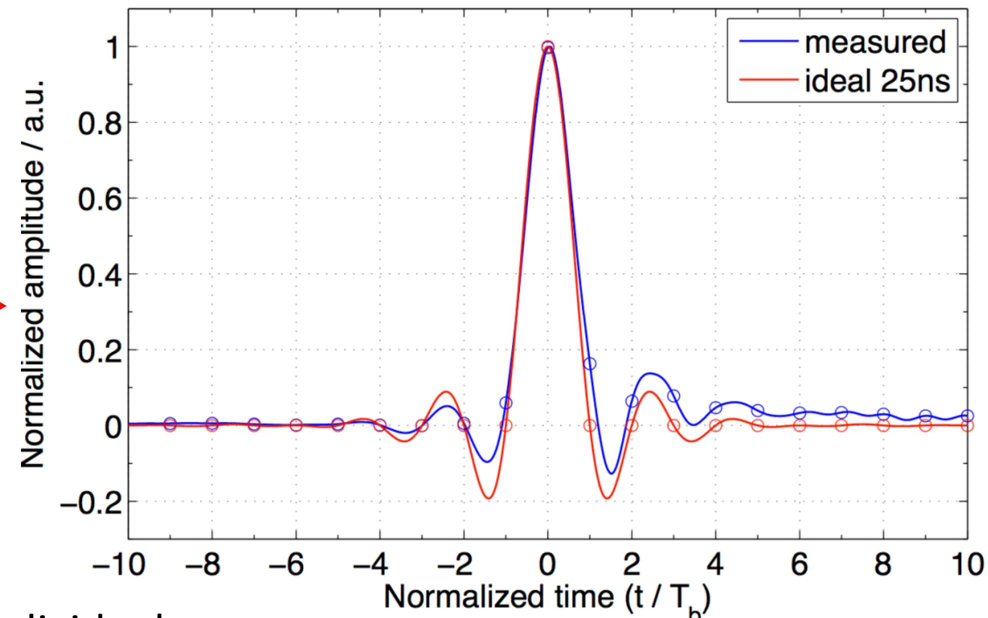
- Motivated by appearance of single bunch instabilities
- Used operationally for squeeze and 25 ns spacing tests in Run 1
- Available, but not re-commissioned in 2015

Condition for $h(nT_b) = 0$
→ symmetry of roll off



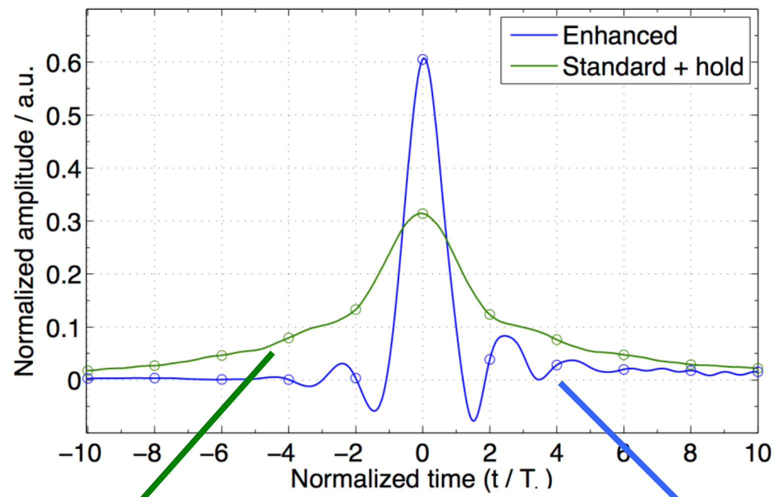






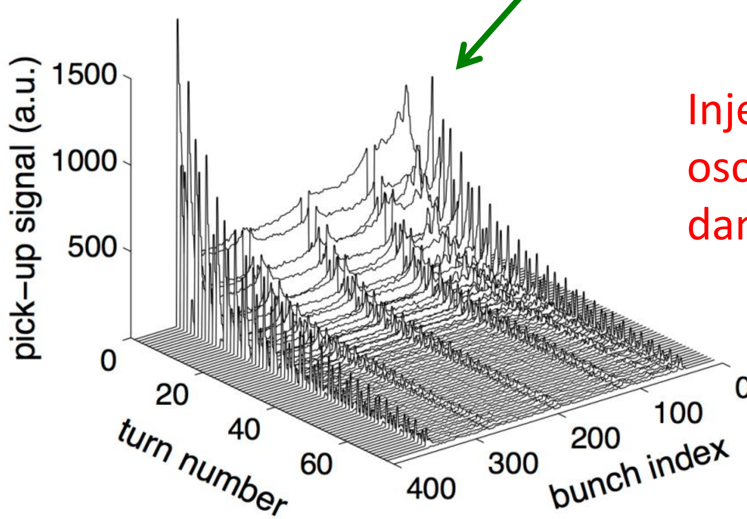
Requires careful measurements and individual compensations for the eight modules to be perfect

Performance with Bunch Trains in LHC 2012

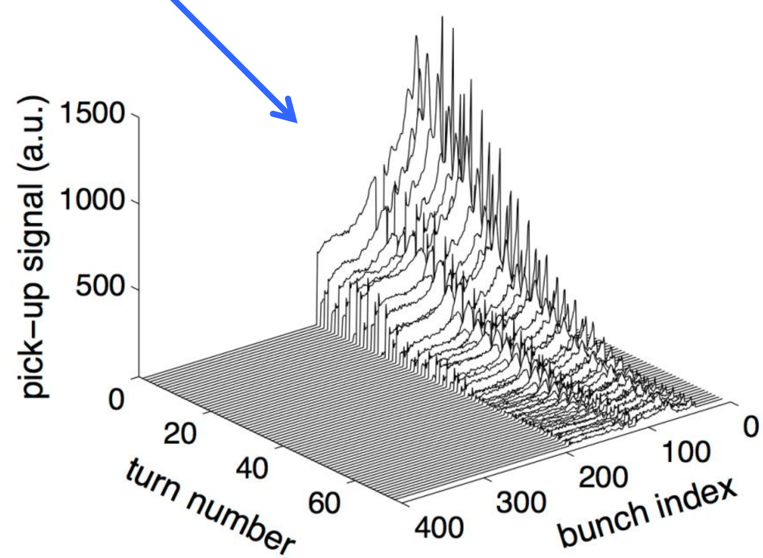


50 ns bunch spacing
standard + hold
144 bunches (4x36)

25 ns bunch spacing
enhanced bandwidth
144 bunches (2x72)



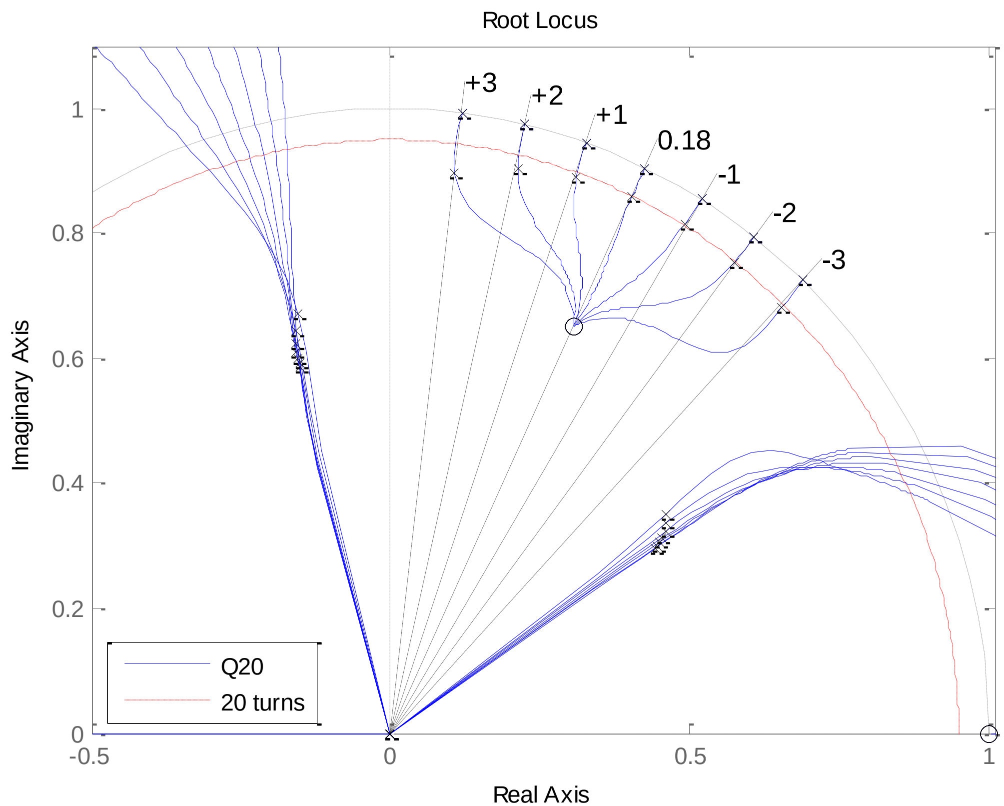
Injection
oscillation
damping



More pick-up noise is injected with the enhanced settings

IPAC’13, WEPME43

Increased Tune Acceptance



Example: SPS
With three synchrotron sidebands

G. Kotzian (CERN)
J. Fox, C. Rivetta (US-LARP)

New digital filters as considered for the SPS Q20 optics and the Wideband feedback relevant applicable to LHC to improve acceptance of tune variations and cover synchrotron side bands

→ Very relevant for running LHC at high beam/beam tune shifts

→ Current signal processing is limiting us to a narrow tune range

REDUCING THE SYSTEM NOISE AND UNLOCKING POTENTIAL OF ADT FOR BEAM DIAGNOSTIC

Pickups available for ADT after LS1

effectively no change in 2015 with respect to Run 1

B1 horizontal	Q10L	Q9L	Q7L	Q7R	Q9R	Q10R
	β = 28 m	β = 127 m	β = 112 m	β = 78 m	β = 16 m	β = 158 m
		existing	existing	new		new

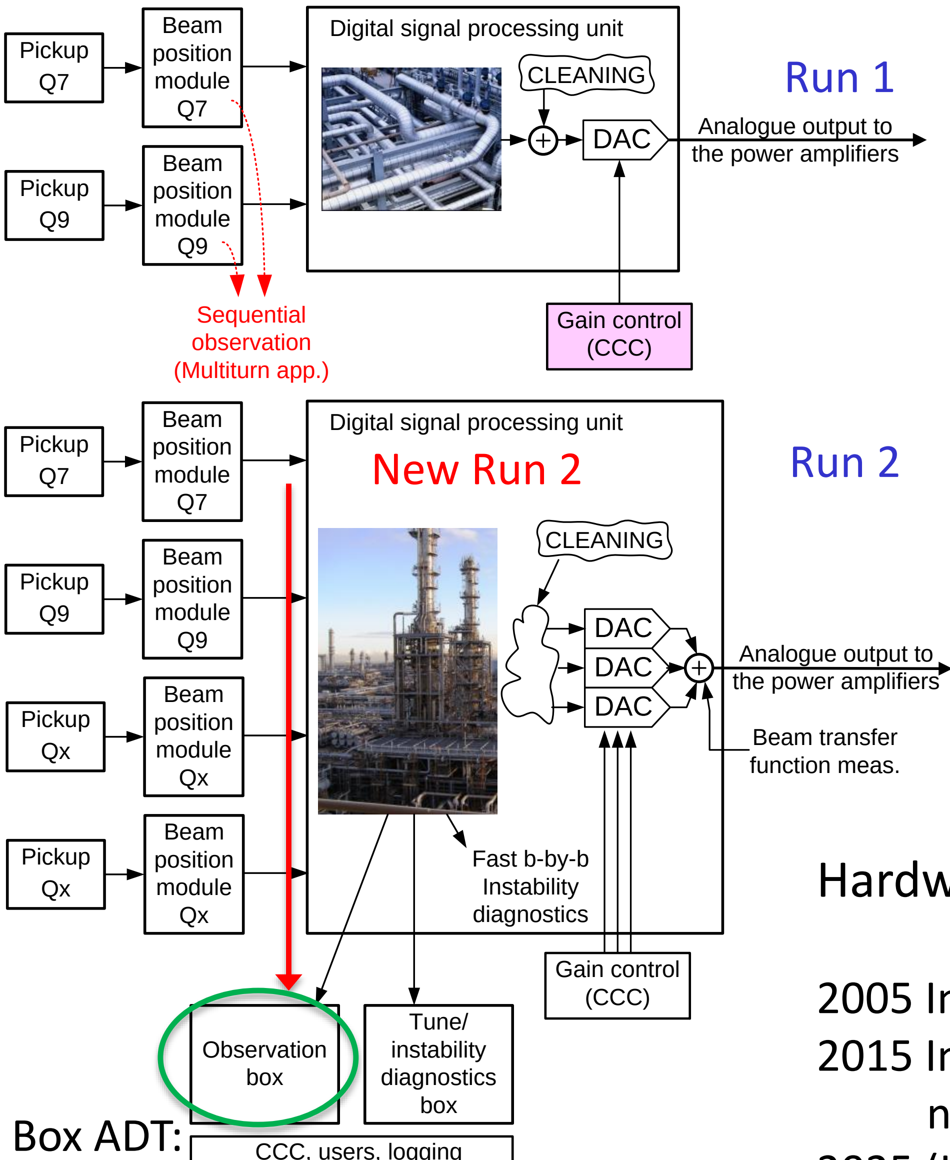
B1 vertical	Q10L	Q9L	Q7L	Q7R	Q9R	Q10R
	β = 172 m	β = 25 m	β = 52 m	β = 127 m	β = 138 m	β = 38 m
	new		new	existing	existing	

B2 horizontal	Q10L	Q9L	Q7L	Q7R	Q9R	Q10R
	β = 164 m	β = 17 m	β = 60 m	β = 173 m	β = 106 m	β = 30 m
	new		new	existing	existing	

B2 vertical	Q10L	Q9L	Q7L	Q7R	Q9R	Q10R
	β = 36 m	β = 140 m	β = 169 m	β = 23 m	β = 34 m	β = 181 m
		existing	existing	new		new

New pick-ups to be made operational during 2016 → Improvement possible right of IP4 by the ATS optics (higher beta functions) in High Lumi era → improved S/N

Evolution of ADT LLRF hardware



Obs Box ADT:
Potentially streaming data from 40 channels at 2 GB/s each

Goals and Changes from Run1 to Run 2

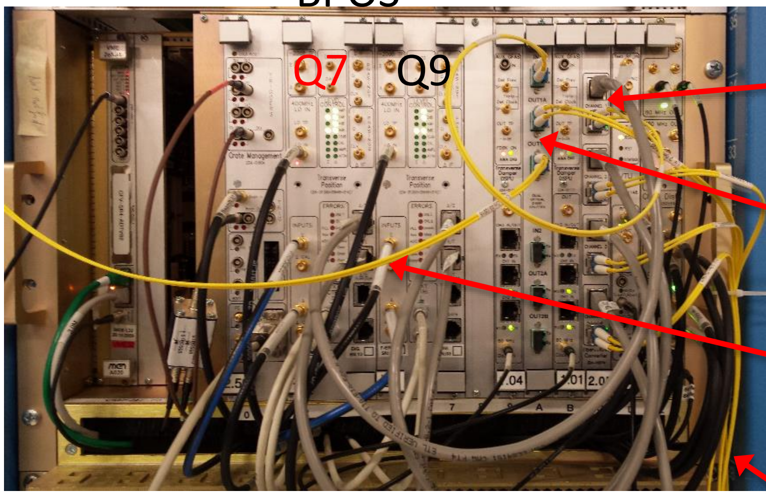
- need to combine four pick-ups
- Separate control for all features with high resolution calls for independent output DACs
- Improved S/N performance
- digital links to observation Box

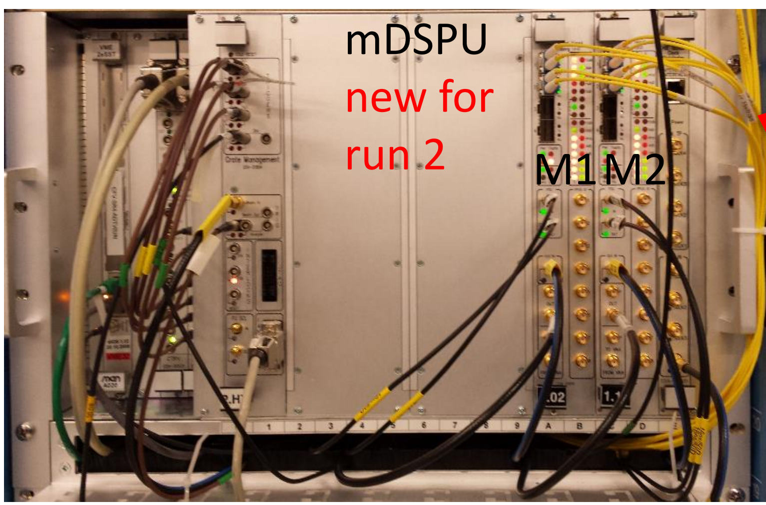
Hardware generations:

2005 Initial VME hardware for LHC start-up
2015 Improved new electronic hardware, no change of platform
2025 (LS3) change of platform, hardware for High Lumi

Implementation for ADT in 2015

BPOS





Electro-optic conversion (new 2015)

Optical splitter

Link to Obs Box (Q7)

Links connecting BPOS VME modules to mDSPU VME processing module generating ADT drive signal

Shown: 1 beam, 1 plane → x4

Envisage to move to new platform in 2025 (in LS3 ?)

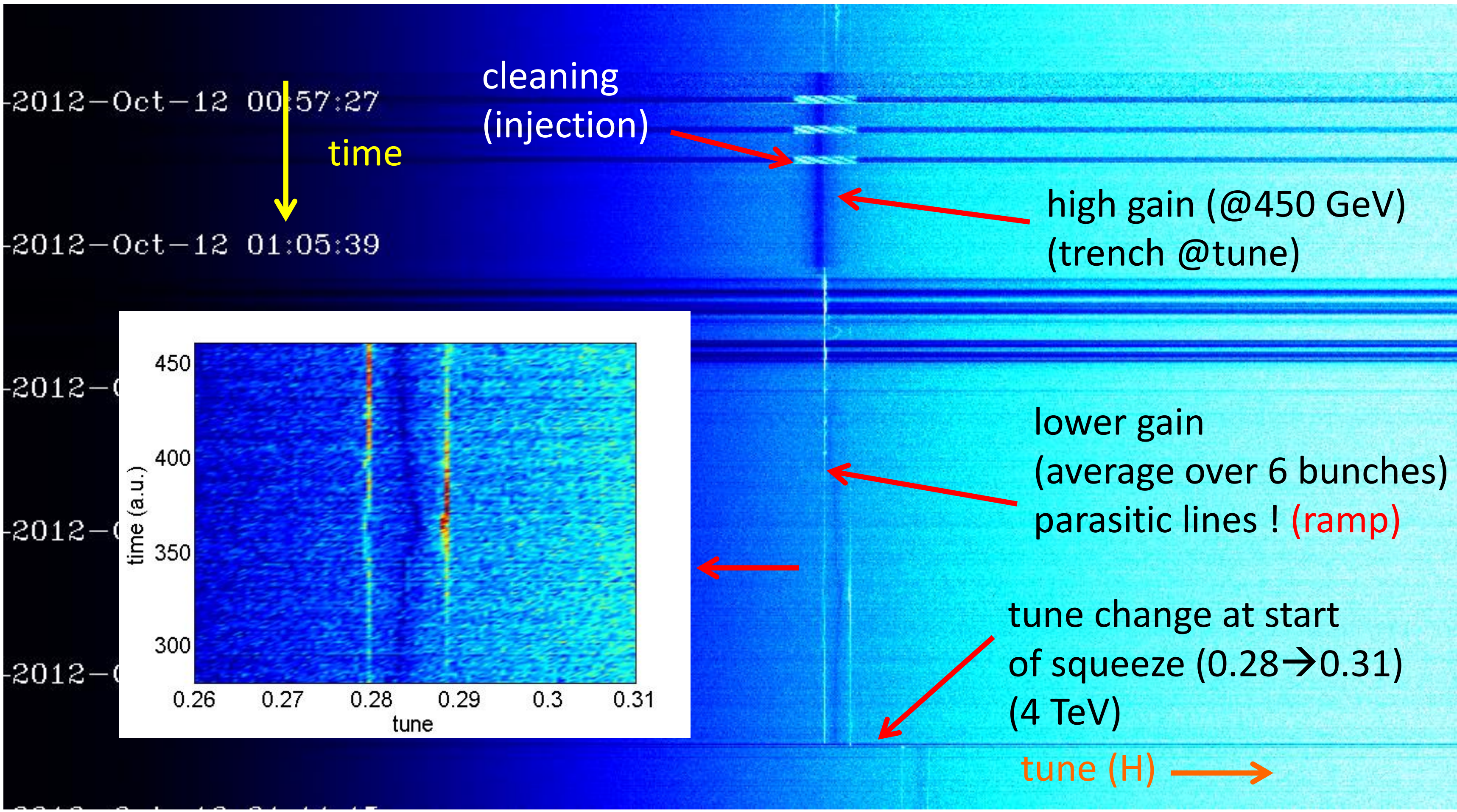
RF Observation Box

- System components
  - SuperMicro 6028U-TR4+ server (**2U** rack-mountable)
  - 2 Intel Xeon E5-2620 v3 (**12 cores** total)
  - **128 GiB** ECC memory
  - **4** PCIe BE/CO **SPEC** cards with SFP to GTP interface
    - DIO FMC module for hardware triggers (optional)
  - **Timing card CTRP** (through carrier, optional)
  - Modern **GPGPU** (optional)

- Plenty of room for **expansion** if needed
  - Up to 36 cores total
  - Up to **1.5 TiB** ECC RAM (≈ **30 minutes** of payload **data**)
  - Up to 10 SATA3 HDDs

Long term investment to harvest data from the feedback systems
The data are key to understanding beam instabilities and tackling their mitigation
→ Extremely relevant to prepare for High Lumi pushed bunch intensities

Big data: Tune Measurement with ADT (LHC)



Based on recording of 6 bunches (horizontal plane)
(also considering and tested excitation by short burst gated on 6 bunches)

F. Dubouchet et. al. IBIC'13, TUPF29

More to come with Obs Box

FACING NEW CHALLENGES FOR HIGH LUMI LHC

Instabilities: Potential for New Feedbacks

PS:

- ❑ Instability for high intensity TOF beams

SPS:

- ❑ Single bunch vertical instability for high intensity 25 ns beam

LHC:

- ❑ Instabilities at injection for nominal 25 ns beam
- ❑ Instabilities at flat top for nominal 25 ns beam
- ❑ Control of the doublet beam for scrubbing

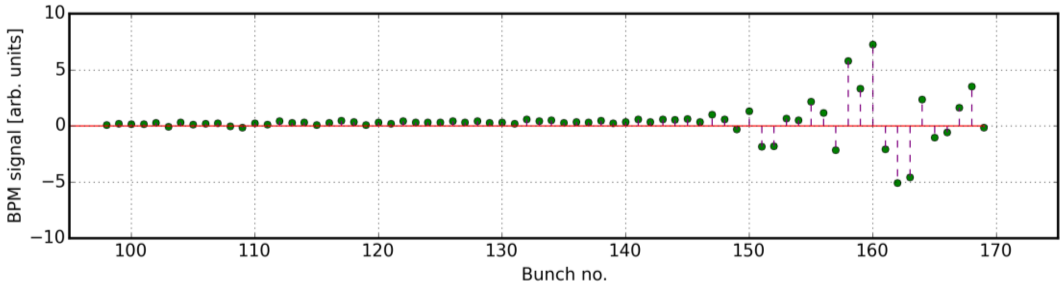
HL-LHC:

- ❑ Instabilities from crab cavity HOMs

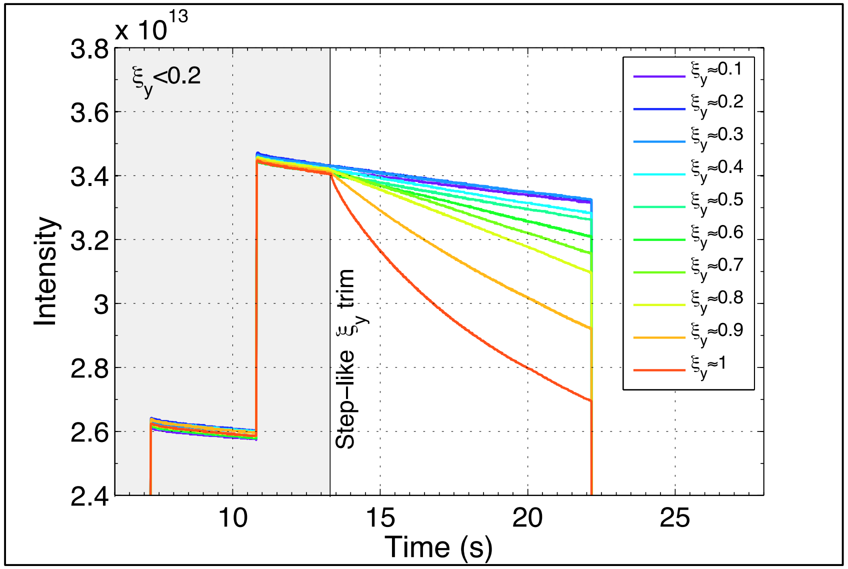
	Required bandwidth	Rise time
PS (TOF)	~ 800 MHz	50 turns
SPS (h plane)	~ 20 MHz	750 turns
SPS (v plane)	→ 500 MHz	150 turns
LHC (injection)	→ 2 GHz	250 turns
LHC (squeeze)	> 20 MHz ?	10’000 turns
LHC (doublet)	> 100 MHz ?	50 turns
HL-LHC (crabs)	→ 1.75 GHz	10’000 turns

See K. Li, 15.10.2015, LIU-HighLumi Day, https://indico.cern.ch/event/437662/

Instabilities SPS (example)



SPS vertical single bunch
Instability (e-cloud)
With intra-bunch component
→ current feedback insufficient



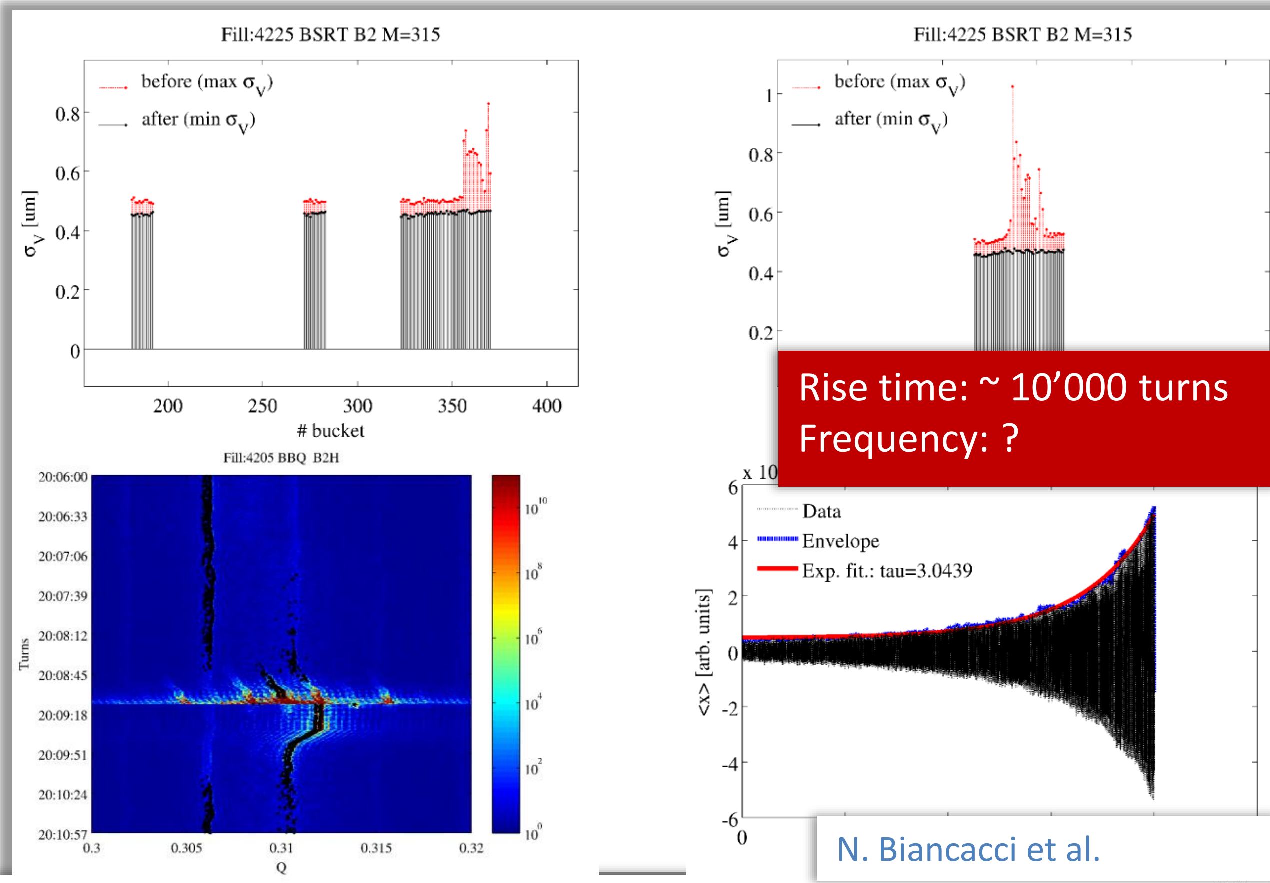
SPS ecloud under control

- Scrubbing
- Future Coating

Transverse feedbacks needed and can help to run with lower chromaticity

H. Bartosik et al.

LHC 2012 experience



Rise time: ~ 10’000 turns
Frequency: ?

N. Biancacci et al.

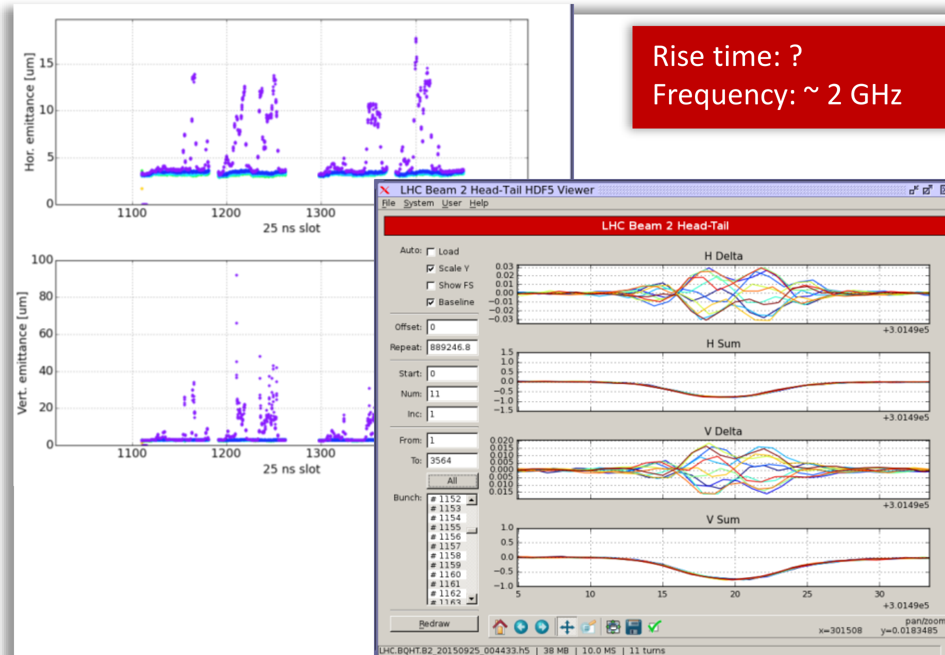
2012 experience & recent observations → will become again critical with High Lumi bunch intensities

- octupoles increasing to 546A during squeeze, 470A after.
- regularly see instability in B2V during squeeze at ~9m.
- **Typical patterns of emittance blowup from before squeeze (black) and after squeeze (red).**
- Has to be stabilized by moving chroma 10 → 15

Instabilities hardly manageable

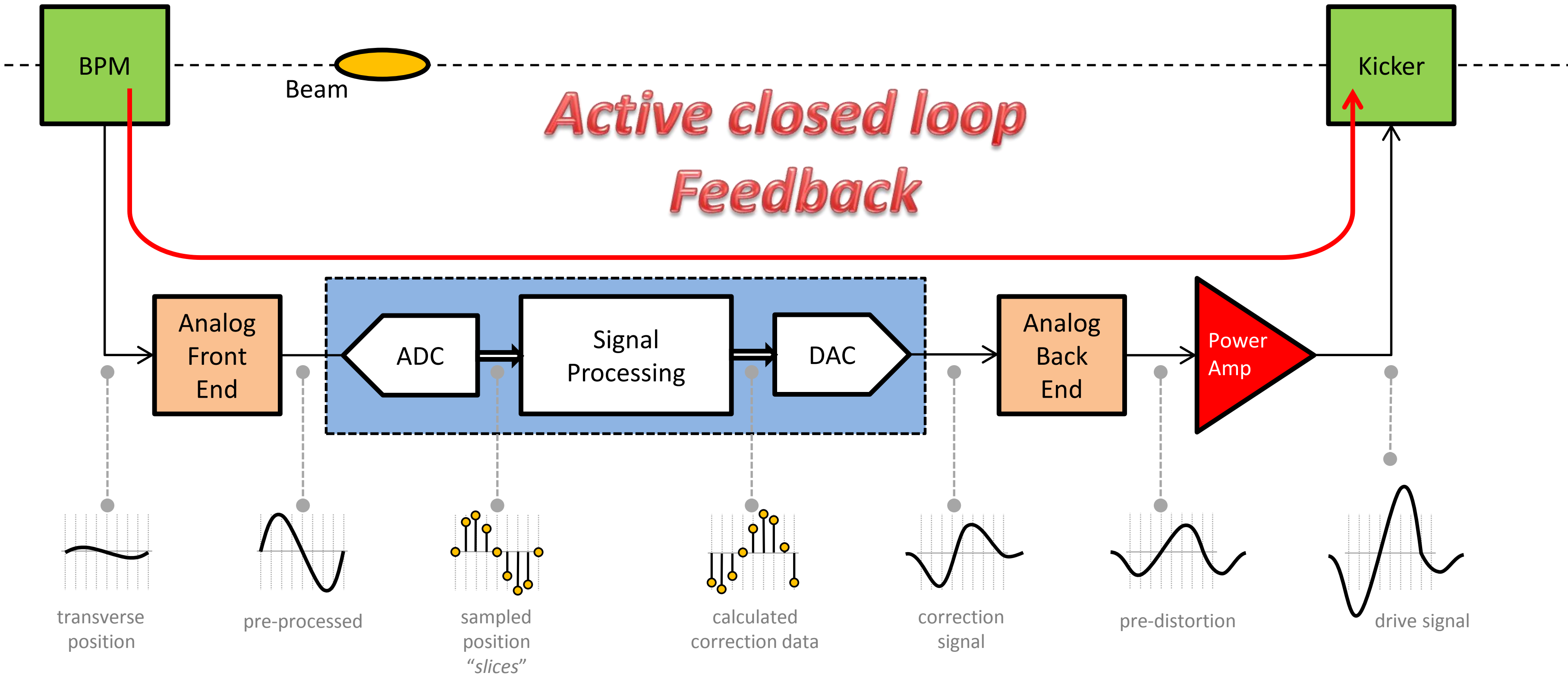
LHC:

- ❑ The pure current impedance model is expected to give rise to instabilities that can be handled by current means of stabilization (octupoles, perfect damper) for single as well as coupled bunch.
- ❑ When other sources of instability are folded in, the requirements on the means of stabilization drastically increase.
- ❑ Mid/end squeeze – not cured by present damper. Likely due to e-cloud – limitations to be re-assessed after more conditioning.
- ❑ Injection – instabilities and blow-up
- ❑ High Lumi LHC will see 25 ns stability issues combined with high intensity bunch currents → be prepared



- E-cloud instabilities force operation at chroma ~15, octupoles ~20A, damper gain ~0.25 (~ 10 turns) – highly sensitive to damper settings and coupling
- Change of WP required – Qh: 0.275, Qv: 0.295
- Still sporadically blow-up observed

Intra Bunch Transverse Feedback



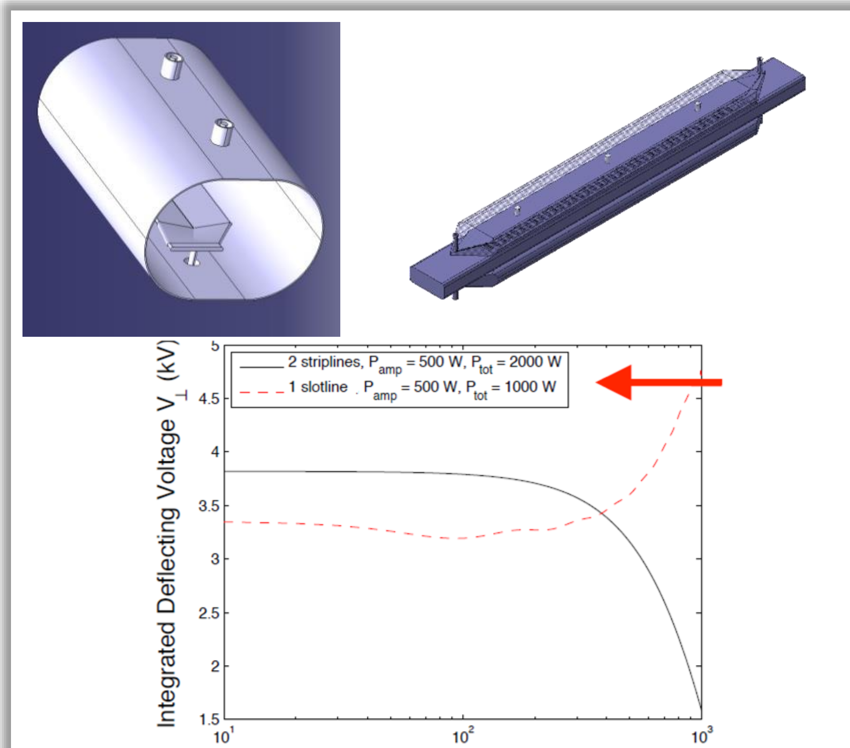
Wideband and intra-bunch can be considered as an additional mitigation measure

Wideband feedback system for the SPS

The project is essential to acquire expertise on:

- How to numerically model and study wideband feedback systems for mitigation of intra-bunch coherent motion (with noise mechanisms, numeric processing effects and saturation mechanisms to understand system design trade-offs)
  → available for LHC/HL-LHC
- Prototyping of high speed electronics (4Gs/s digital signal processing system) & exploration of control algorithms
  → Architecture developed is reconfigurable for LHC/HL-LHC.

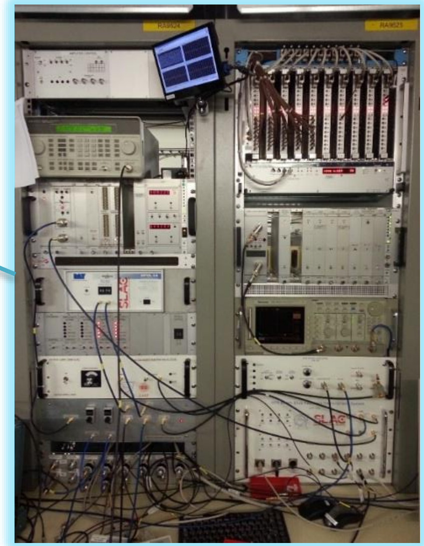
Design of wideband kicker systems with evaluation of power amplifiers at 5-1000 MHz, 250 W
→ Would need extrapolation towards increased power and bandwidth for kickers and power amplifiers for LHC/HL-LHC – needs electromagnetic kicker design



Wideband stripline and slotline kicker designs.

J. Cesaratto et al., CERN ACC-Note-2013-0047/SLAC-R-1037
CERN-US LARP

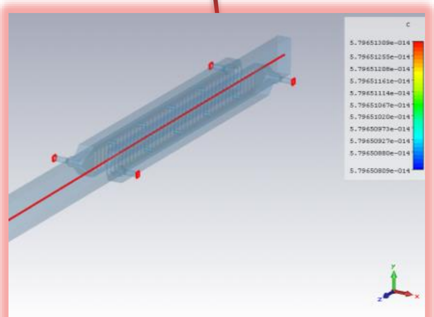
Wideband feedback system (SPS)



Complete processing channel from pickups through kicker, running a digital reconfigurable system up to 4 GS/s is installed and ready for use at 3.2 Gs/s

(SLAC – US LARP)

2 x Striplines



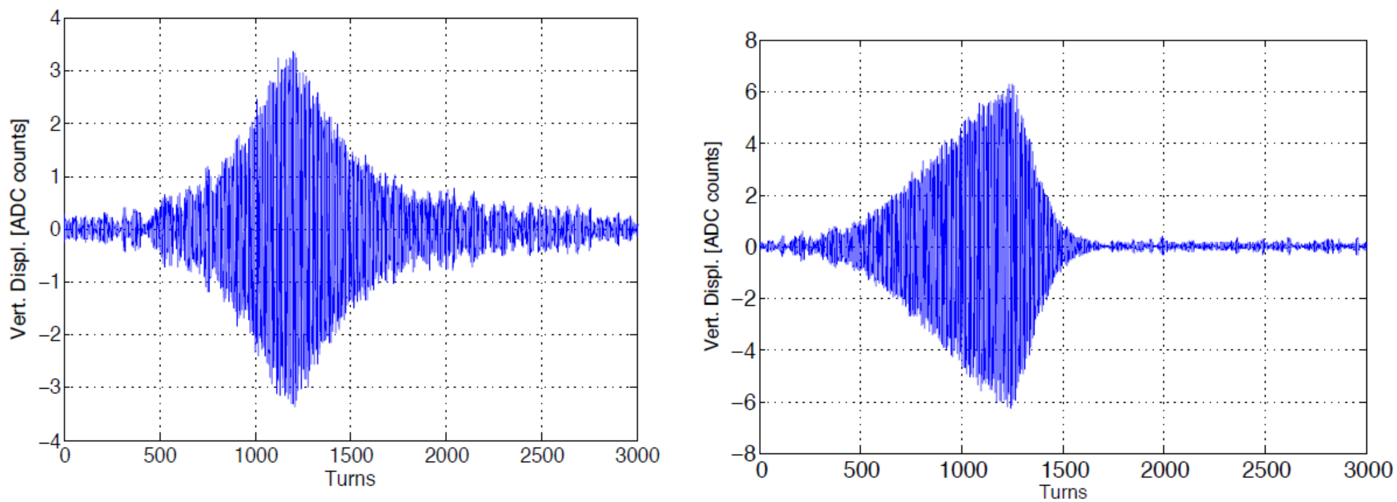
1 x Slotline

The two installed stripline kickers will be augmented by the slotline kicker in 2016, and the two installed 5 - 1000 MHz amplifiers will be augmented by two more wideband amplifiers this winter. This doubling of kicker voltage is critical in evaluating the system performance in the 2015/2016 MD series

Possibility to visit this installation as part of the CCC tour Friday p.m.

SPS system being used in MDs

System used for MDs with limited power kickers, has controlled unstable beams
→ now developing control methods for higher intensity beams



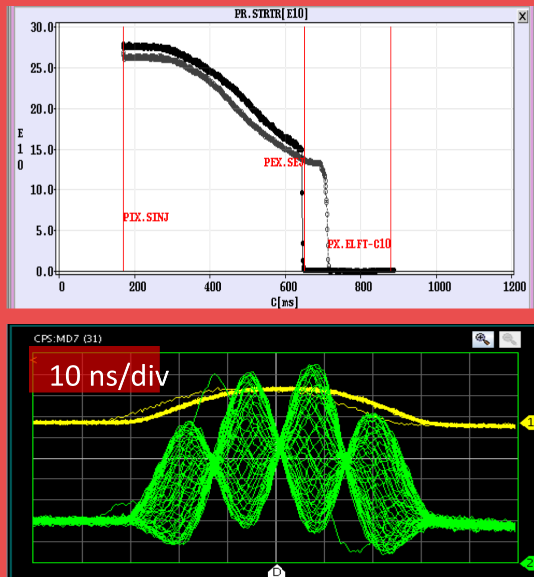
- Grow/damp SPS Measurement - Damping Gain G=4 (left) G=16 (right)
- Intensity $1.1x10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models

More recent results will also be shown in 2 weeks at the 5th Joint HiLumi LHC-LARP Annual Meeting

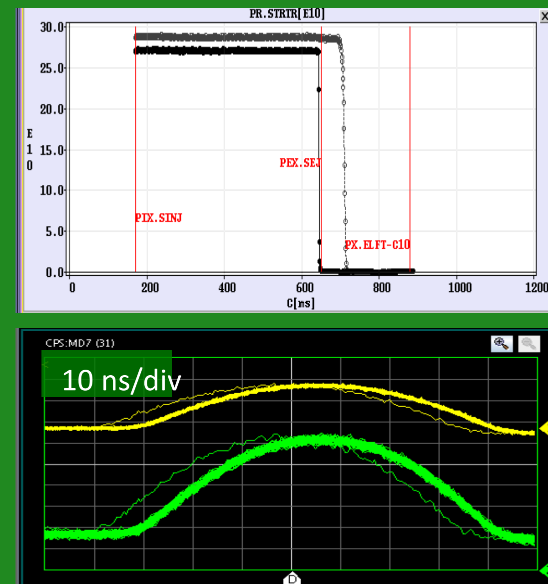
J. Fox et al, IBIC 2015 Melbourne

Essential to demonstrate intra-bunch Feedback at SPS on short bunches in preparation of any implemenation for HighLumi LHC or other accelerators

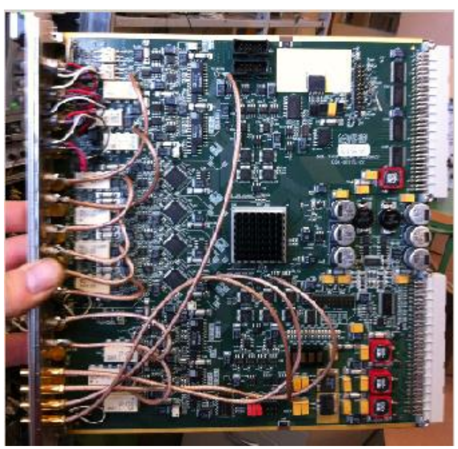
Intra-bunch feedback at work (CERN PS)



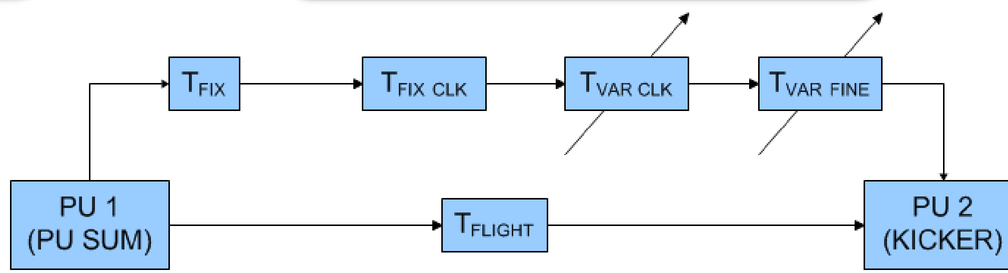
PS TFB OFF



PS TFB ON



Similar results also at JPARC



1.4 GeV → 26 GeV

Challenge:

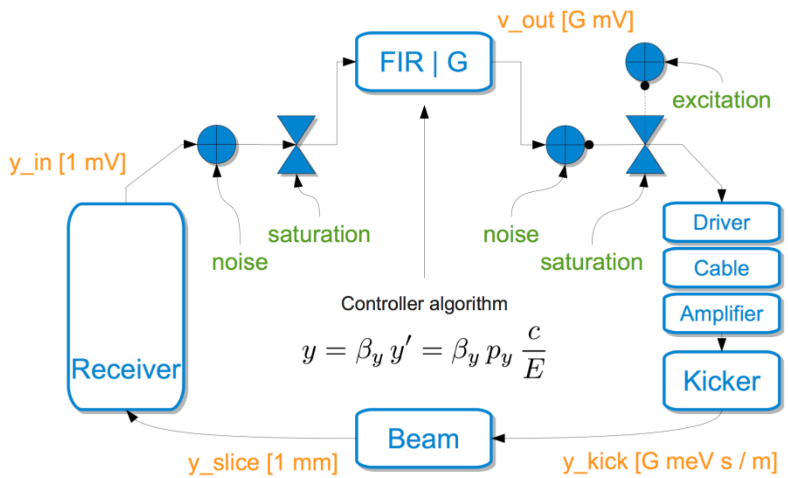
Time of Flight Compensation

Fully digital implementation

A. Blas et al. IPAC'13 WEPME011

D. Perrelet (CERN BE-RF)

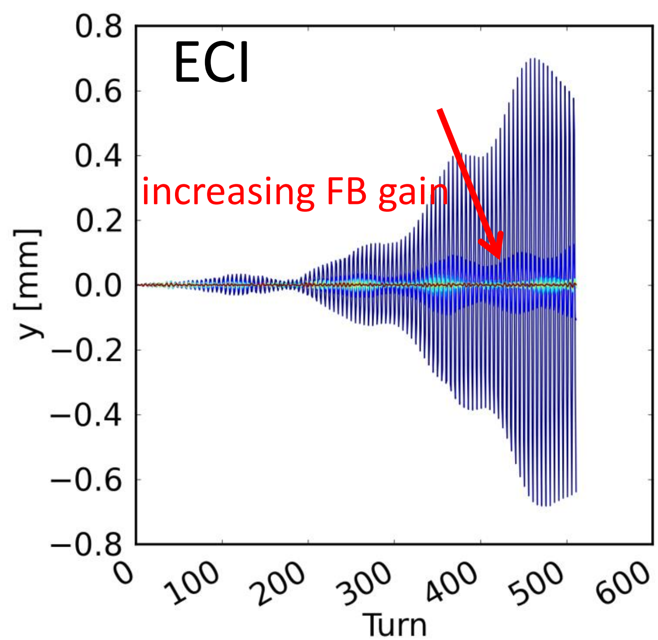
Simulations with Feedback

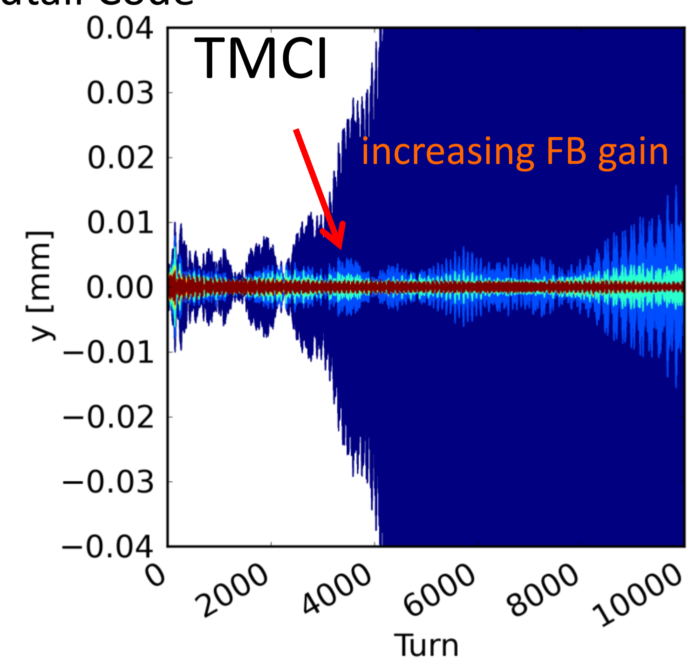


Bandwidth need at SPS injection 450 GeV/c from simulation (2.7 ns bunch length)

- ECI: 500 MHz
- TMCI: 200 MHz

CERN Headtail Code





K. Li et al., IPAC’13 WEPME042

Options for kickers for New Feedback system in LHC for High-Lumi Era

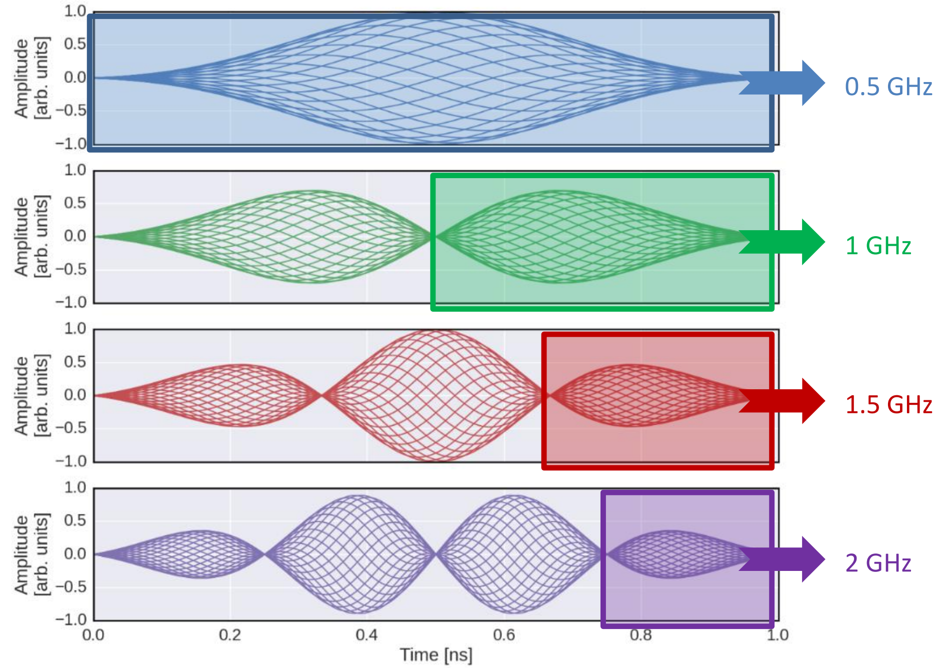
Damper kick strength/voltage:

With 5 m space – consider installation of 4 slotline kickers → V ~ 37 kV with 2 kW amplifiers at 1 GHz

- Slotline dimensions are smaller for LHC compared to SPS – can gain a factor 2 in kick strength
- Bandwidth: Slotline dimensions are smaller for LHC – can gain a factor 2 in frequency reach

Options:

1. Extension of current system:
   long stripline at 40 MHz for true bunch-by-bunch damping
2. Band-by-band approach:
   Stripline at 400 MHz in combination with slotlines at 800, 1200, 1600, 2000, 2400,… MHz; cavities with transverse modes could also be considered



Run 2 experience and collaboration with the instability team will show for which scenario we will have to prepare

Conclusions

- Transverse feedback (ADT) is essential for beam stability and emittance preservation in LHC since 2010 including with colliding beams
- The ADT system will evolve until LS3 with new pick-ups and LLRF hardware and improved signal processing to address bandwidth limitations and to reduce the system noise
- Addition of hardware for data collection will provide instability diagnostics to contribute to assess the need for further feedback upgrades or new feedbacks for the LHC High Lumi era
- The US-LARP supported R&D activity in the SPS provides a path to address high frequency intra-bunch instabilities that can be a limitation in the future High Lumi LHC era
- The successful demonstration of intra-bunch feedback in the SPS would constitute a major advance in Accelerator Technology beyond SPS and High Lumi LHC